Edited Version

Mechanical Design of Social Robot Nancy

S. S. Ge, M. R. Safizadeh, and Y. Li

Abstract— **This paper presents the mechanical design of a social robot, Nancy, developed by Social Robotics Laboratory, Interactive and Digital Media Institute, National University of Singapore. The objective of our project is to introduce the social robot which is capable to interact with people, especially the elderly, based on fundamental, functional and social tasks. We developed Nancy with multi-module structure and 32 degrees of freedom (DOFs), including 24 and 8 DOFs in upper-body and lower-body, respectively. 8 DOFs are considered in each arm to make Nancy able to imitate human limbs' motion. Nancy's head involves eye and eyelid motions with 3 DOFs which is on top of a 2-DOFs neck. The wheeled-base is designed in such a way to facilitate the multi-directional movements for Nancy. One of our main objectives in Nancy's mechanical design is to obtain powerful and smooth motion, light-weight joints and simple kinematics. They are achieved by Bowden cable-pulley mechanism driven by actuators located in lower-body. Accordingly, all joints are designed to have intersected axes. Most joints are driven by brushless D.C. motors embedded with electrical brake system to stabilize the robot, especially in case of power loss.**

I. Introduction

Recently, to reduce the social distance between the robots and human society, scientists' attention on the development of social robots has significantly increased. Social robots are expected to interact with the environments (including human) using the basic, functional and social tasks as listed in Table I. Intensive researches in various universities and research centers have been conducted to improve the robot-human interactions through multi-discipline studies, such as mechanism design, feature design and control system design. Among all mentioned aspects, mechanical design may be the most important factor to make a robot attractive and is thus crucial for researchers to pay attention to. In a social application, a robot's feature is usually expected to be friendly and preferably anthropomorphic. Therefore, the humanoid robot, particularly human-size robot, has been extensively studied by researchers. In this regard, it would be easier for human to interact naturally with a human-size robot, which consists of enough DOFs to imitate the human motions [1].

TABLE I
Social Robotic Tasks

Tasks	Descriptions
Fundamental Tasks:	Basic Motions
	Speech Recognition
	Sound Localization
	Speaking
Functional Tasks:	Object Avoidance
	Navigation
	Face Tracking
	Object Recognition
	Object Localization
	Picking and Placing the Object
Social Tasks:	Tapping
	Hand-shaking
	Hugging
	Chatting
	Physical Assistance

In robotics community, many researches have been carried out to develop the humanoid and social robots [2], [3], [4], [5], [6], [7]. For instance, the new generation of Honda-Humanoid robot ASIMO with 120cm in height, 52Kg in weight and 26 in DOFs was exhibited with new intelligent control system which makes it able to walk continually while changing the direction [8]. Additionally, the Humanoid Research Group at Intelligent Systems Research Institute in Japan has had the intensive research results on humanoid robot HRP-2, which is the first human-size robot that can lie down and get up in addition to capability of walking and climbing on stairs. It has dimensions of $1539 \times 621 \times 355$ (mm) in height, width and depth, respectively, 30 DOFs and weight of 58Kg [9]. HRP-2 was followed by HRP-3, which has a similar size, more DOFs, and improved joints configuration in hip and wrist to achieve smooth motions [10]. HRP-2 and HRP-3 are the human-size robot in male features and they are not capable to conduct human-robot interactions. Therefore, the next generation of HRP robot (HRP-4) was designed in feminine appearance and size with capability of sound recognition and facial reactions.

Our social robot project aims to develop a social robot, which plays the nurse role to take care of the elderly. Nancy (Figs. 1 , 2 and 4) has been designed and developed to accomplish the fundamental, functional and particularly

This study was supported by Singapore National Research Foundation, Interactive Digital Media R&D Program, under research grant R-705-000-017- 279.

S. S. Ge is with the Social Robotics Lab, Interactive Digital Media Institute and the Department of Electrical and Computer Engineering, National University of Singapore, Singapore 117576, and the Robotics Institute, and School of Computer Science and Engineering, University of Electronic Science and Technology of China, Chengdu 610054, China. email: samge@nus.edu.sg.

M. R. Safizadeh is with Social Robotics Lab., Interactive Digital Media Institute, National University of Singapore, Singapore, 119613 Singapore m.reza.safizadeh@gmail.com.

Y. Li is with the Social Robotics Lab., Interactive Digital Media Institute and the NUS Graduate School for Integrative Sciences and Engineering, National University of Singapore, Singapore 119613. email: liyanan84@nus.edu.sg.

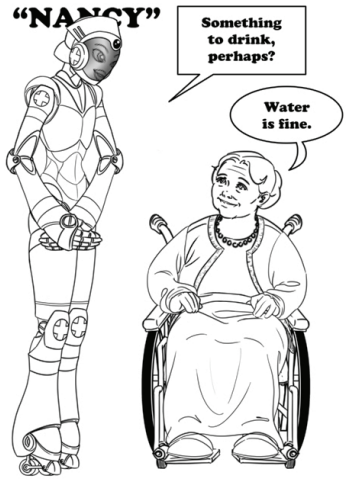

Fig. 1. Social Robotic Nurse: Nancy

social tasks such as tapping, hand-shaking and hugging. Nancy is embedded with high-level artificial intelligence (AI) and adaptive control systems [11]. It has a friendly and human-like appearance, soft skin, sufficient DOFs to be capable to interact with its environments.

A mechanism is required to make Nancy able to emulate the human motions with higher functionality, flexibility, power and safety. The mechanism of Bowden cable-pulley is proposed in order to achieve the following highlighted objectives:

(i) Imitation of human muscles actions using cables.
(ii) Increasing options in choosing different drivers with various power, weight, size and functionality.
(iii) Enhancing the robot balance by placing the majority of drivers in legs and feet.
(iv) Increasing the flexibility on varying the robot's power by changing the driver types and the pulley sizes.
(v) Isolating the drivers in order to avoid any noise and disturbance resulted from drivers.
(vi) Decreasing the upper-body weight by shifting the drivers from joints.
(vii) Increasing the flexibility of the proposed mechanism in different robots' scales.
(viii) Simplification of kinematics as well as control system using the intersected axes in each joint.

Despite all mentioned advantages of proposed cable driven mechanism, there were some encountered problems in assembly and control system. Particularly, the connection and assembly of driver and driven pulleys using Bowden cable is not as easy as belt, chain or gears and it requires more precision and time . Additionally, due to cable elasticity, the special cable with low elastic properties and two encoders installed on each mutual driven and driver pulleys are considered to compensate the slippery and elastic uncertainties.

Many researches on robotic mechanism design have been conducted to simplify the kinematics by intersecting all axes in each joint, especially on hip, ankle, shoulder and wrist. As a result, the researchers came up with two common types of motors, say, servo and harmonic. In the case of servo motor, robot does not have enough power to achieve some tasks, such as crouching and holding objects. In the case of harmonic motor, they are usually too heavy [7], [9], [10]. On top of that, both types of drivers do not include the brake system to prevent the robot from falling in case of power loss. Comparatively, since most DOFs in Nancy's joints - hip, knee, ankle, shoulder (yaw) - are driven by pulleys and powered by the high power brushless D.C motors with brake, it has enough power to bend, crouch and lift objects, efficiently and safely. It can also keep its balance when the power is off with the help of the equipped brake system.

Besides, there are several existing robots that contain joints (either upper or lower-body) driven by cable mechanism [12], [13], [14], [15], [16]. In Nancy's development, we design a new configuration of cable-pulley mechanism to drive all joints except neck and torso. Since most of drivers (except torso, neck and wrist) are located in lower-body and majority of Nancy's weight is transferred to lower-body, the wheeled feet mechanism is introduced to the system. In this sense, Nancy follows most of human's leg motions (except yaw axis in hip), which is not the case in other existing wheeled robots [17].

II. Overview of Mechanical Design

The prior step in robot design is to identify the expected applications, features and environments that it interacts with. In this project, Nancy's mechanism was designed according to the biological inspiration in order to bring Nancy into reality of human being to be felt naturally. The biological architecture was embedded with artificial intelligence (AI) to accomplish the defined and expected tasks listed in Table I. In order to imitate human's reaction and motion using AI, the human embodiment equipped with control system is essential to be modeled and built. For example, if there are two objects in front of a person and a 3-DOF robot's arm in the same distance in respect to them, the trajectories which they reach the objects are totally different because of different DOFs and link lengthes. Thus, the biological architecture design is the basic step to train the AI to perform like human brain. However, the biological design is not only about the size and DOFs but also the driver mechanism. In this work, the cable mechanism was proposed to act as human's muscle-tendon system.

Several studies on human anatomy and social tasks have been done in order to define the human's joint motions, DOFs, motion ranges (Tables II and III), limb length, cable strength and pulley reduction. Nancy is designed with 160.7cm in height, 42cm (shoulder to shoulder) and 59.8cm (feet side to side) in width and 64.14Kg (14.53Kg for light upper-body) in weight (Figs. 2 and 3). It also has totally 32 DOFs which are divided to upper-body (24 DOFs) and lower-body (8 DOFs). To simplify the kinematics, axes intersection is applied to several joints, such as wrists, elbows, shoulders, neck, hips and ankles. Moreover, Nancy has an extra DOF to emulate the scapular motion, and it contains three DOFs in

TABLE II

NANCY'S SPECIFICATIONS

Dimensions	Height	1817mm
	Width	462mm
	Depth	397mm
Weight	81Kg	
DOF	Head	3 DOFs
	Neck	2 DOFs
	Scapula	2×1 DOFs
	Shoulder	2×2 DOFs
	Upper arm	2×1 DOFs
	Elbow	2×1 DOFs
	Forearm	2×1 DOFs
	Wrist	2×2 DOFs
	Hand	2×1 DOFs
	Waist	1 DOF
	Hip	2×2 DOFs
	Knee	2×1 DOFs

TABLE III

NANCY'S MOTION RANGES

Joint	Joint Axis	Motion Range (Angle)
Head	Yaw(Eye)	$-35°$ to $35°$
	Pitch(Eye)	$-50°$ to $50°$
Neck	Yaw	$-110°$ to $110°$
	Pitch	$-75°$ to $75°$
Scapula	Yaw	$-120°$ to $30°$
Shoulder	Pitch	$-50°$ to $50°$
	Roll	$-75°$ to $75°$
Upper Arm	Pitch	$-45°$ to $45°$
Elbow	Yaw	$-120°$ to $0°$
Forearm	Pitch	$-50°$ to $50°$
Wrist	Yaw	$-35°$ to $35°$
	Roll	$-15°$ to $15°$
Waist	Yaw	$-90°$ to $90°$
Hip	Pitch	$-30°$ to $60°$
	Roll	$-30°$ to $30°$
Knee	Pitch	$0°$ to $90°$

shoulders in comparison with two DOFs in most of existing robots (Fig. 4).

III. UPPER-BODY DESIGN

Since Nancy is expected to accomplish the complex tasks such as tapping, hand-shaking and hugging, the upper-body should comprise enough DOFs, particularly in its arms. Eight DOFs are considered in each arm to complete the social tasks naturally. In Nancy's design, a modular structure is proposed to facilitate fabrication and assembly. As a result, the upper-body consists of hand, wrist, forearm, elbow, upper arm, shoulder, scapula, neck, head and torso modules.

The DC motor for each joint is selected on the basis of maximum pre-considered object weight (3.2Kg) and structure weight in tasks such as lifting and holding. The

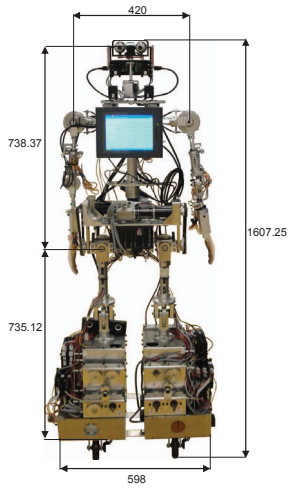

Fig. 2. Nancy's Dimensions (mm) (Front View)

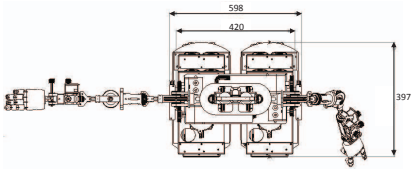

Fig. 3. Nancy's Dimensions (mm) (Top View)

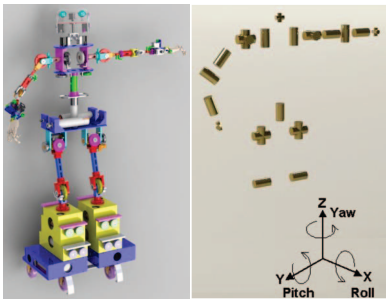

Fig. 4. Schematic View of Nancy's DOFs

maximum torque for each actuator as well as maximum required torque for each arm's joint axis are calculated and listed in Tables IV, Vand VI.

A. Hand Design

Nancy's mechanism is designed and developed on the basis of its applications, therefore, we aimed to consider appropriate DOFs based on its functionality and to avoid the high DOFs which leads to unnecessary complexity in control system. Integrated five fingers with one DOF is considered for the hand design, as shown in Fig. 5.

B. Wrist Design

In order to avoid the complexity of control system, the simple and smooth kinematics was in priority to be taken into account, hence the cable-pulley mechanism helps us to achieve this goal even for small joint. As listed in Table IV,

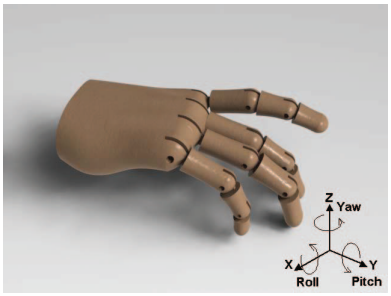

Fig. 5. Hand

TABLE IV
WRIST DRIVERS

Joint	Joint Axis	Driver	Max Torque *(Nm)*	Max Required Torque *(Nm)*	Ratio (Driven /Driver)
Wrist	Yaw	Dynamixel RX-28	2.83	2.78	1/1
	Roll	Dynamixel RX-28	2.83	2.78	1/1

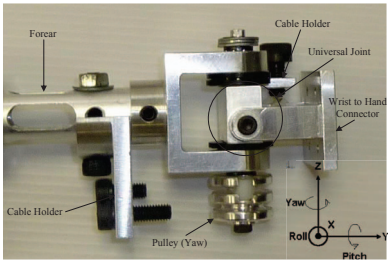

Fig. 6. Wrist

TABLE V
ELBOW AND FOREARM ACTUATORS

Joint	Joint Axis	Driver	Max Torque *(Nm)*	Max Required Torque *(Nm)*	Ratio (Driven /Driver)
Elbow	Yaw	Maxon (Brake)	13.06	10.65	1.12/1
Forearm	Pitch	Maxon	13.06	4.52	0.72/1

two RX-28 servo motors[1] are used to rotate the wrist about yaw and roll axes (Fig. 6).

C. Elbow and Forearm Design

As it is obvious from Figs. 4 and 7, elbow and forearm rotate about yaw and pitch axes, respectively, using the brushless DC motor[2] (Table V) and Bowden cables which are directed to the lower-body. As a result, the mass as well as momentum of inertia about the shoulder joint is extremely reduced by shifting the heavy motors to the lower-body. Furthermore, the pulleys are located at the center of elbow to avoid any unexpected torque around the roll axis (Fig. 7).

[1]Dynamixel RX-28, Robotis, Seoul, Korea.
[2]283867, EC-max 40, 40mm, Brushless, 70 W, Maxon, Switzerland.

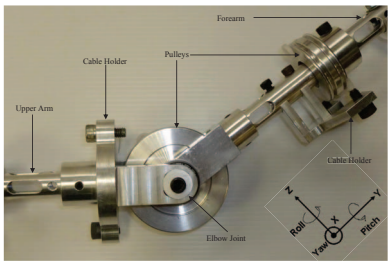

Fig. 7. Elbow and Forearm

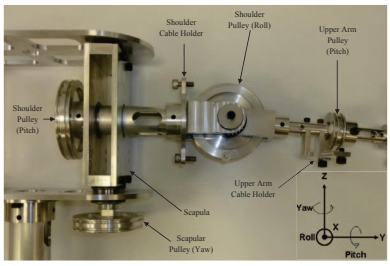

Fig. 8. Shoulder, Upper Arm and Scapula

TABLE VI
SHOULDER, UPPER ARM AND SCAPULA DRIVERS

Joint	Joint Axis	Driver	Max Torque *(Nm)*	Max Required Torque *(Nm)*	Ratio (Driven /Driver)
Shoulder	Pitch	Maxon (Brake)	28.00	25.30	1.52/1
	Roll	Maxon	28.00	23.30	1.52/1
Upper Arm	Pitch	Maxon	13.06	7.15	0.72/1
Scapula	Yaw	Maxon	13.06	5.73	1.32/1

D. Shoulder, Upper Arm and Scapula Design

To guarantee the smooth motions, the high-DOFs shoulder (3 DOFs) was simplified by intersecting three axes (shoulder (pitch), sholder (roll) and upperarm (pitch)) on shoulder joint (Fig. 8). Consequently, the upper arm as well as shoulder (roll axis) is driven by Maxon brushless DC motors[3,4] (Table VI) and the DC motors[4] embedded with brake system[5] drive the shoulder pitch axis. In addition, scapular joint is driven by Maxon motor about yaw axis in order to carry out the hugging task.

E. Head and Neck Design

Head as essential element in social robot, should have enough DOFs in order to communicate efficiently with its partner through the face recognition, emotional expression and motion reaction. Consequently, two digital color cameras[6] are driven by two RX-28 servo motors about the yaw and pitch axes (TableVII), and eyelids are designed to enclose the human facial emotions in Nancy's face (Fig. 9). Besides, two-DOFs differential bevel gear mechanism is

[3]283867, EC-max 40, 40mm, Brushless, 70 W, Maxon, Switzerland.
[4]136198, EC 45, 45 mm, brushless, 150 W, Maxon, Switzerland.
[5]223101, Planetary Gearhead GP 52, C 52 mm, 4-30 Nm, Ceramic Version, Maxon, Switzerland.
[6]Dragonfly2, IEEE-1394a digital camera, Point Grey, Canada.

TABLE VII

HEAD AND NECK DRIVERS

Joint	Joint Axis	Driver	Max Torque *(Nm)*	Ratio (Driven/Driver)
Head	Yaw	Dynamixel RX-28	2.83	1/1
	Pitch_1	Dynamixel RX-28	2.83	1/1
	Pitch_2	Dynamixel RX-28	2.83	1/1
Neck	Yaw	Dynamixel RX-28	2.83	1/1
	Pitch	Dynamixel RX-28	2.83	1/1

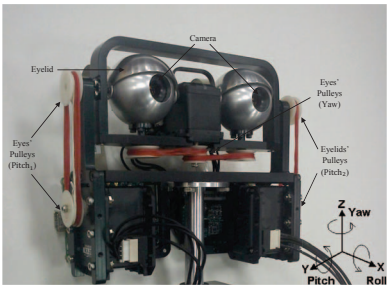

Fig. 9. Head and Eyes

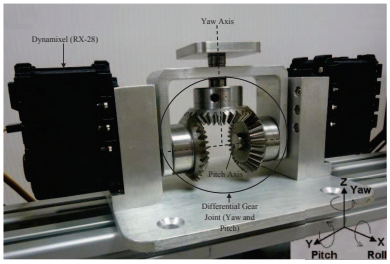

Fig. 10. Differential Gear Mechanism for Neck

contrived for the neck motions to compensate the following deficiencies of other conventional neck mechanism (pan and tilt mechanism).

(i) While the joint axes are not crossover on the neck pitch axis, the system encounters the complexity of kinematic analysis.

(ii) Since mechanism and driver for yaw rotation are offset with the pitch axis in some distance, it causes extra momentum of inertia in nodding motion about the pitch axis and vice versa.

(iii) In order to compensate the head inertia in nodding motion about pitch axis, the powerful and thus bigger and heavier driver is required.

Two RX-28 servo motors work mutually to rotate the head around yaw and pitch axes. They generate powerful and fast motion with minimal momentum of inertia around respective axes (Fig. 10).

IV. LOWER-BODY DESIGN

Since the lower-body motion affects the whole body's motion control accuracy, Nancy's lower-body is designed in

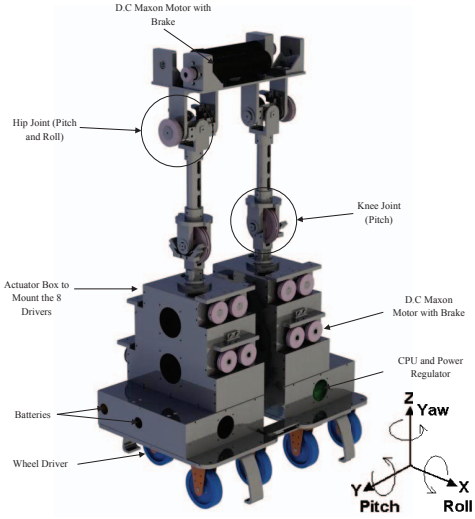

Fig. 11. Lower Body

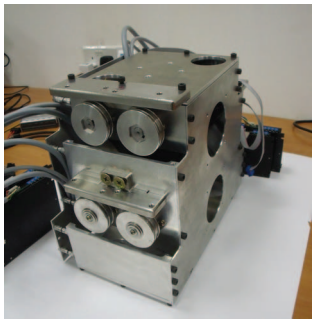

Fig. 12. Container of DC motors

such a way to have accurate and smooth motions with the proposed mechanism. In this design, most drivers, controller boards, and wires are positioned in the lower body, so enough spaces that can contain all these components must be taken in to account. Meanwhile, this large space should not interfere Nancy's kinematical and dynamical capabilities to perform human's walking motion. Moreover, a suitable shape design as well as material properties are considered for all the parts in the lower body, especially ankle's parts, in order to bear the whole upper body, electrical components and driver weights. According to the stress and fracture analysis for some critical joints, aluminium alloy 6061 and stainless steel (SUS 303) are chosen for the lower-body. All parts are modeled in SolidWorks (2009). Optimized sizes are acquired based on optimal spaces, electrical component sizes, positions and minimal wire lengths.

The lower-body contains eight DOFs that are symmetrically divided to two legs to imitate hip and knee's motion, with wheeled feet and using similar DOFs to human's except in the hip yaw axis. Since two boxes were designed to contain the majority of heavy and large drivers (Fig. 11 and Fig. 12), box depth prevents hip yaw rotation to rotate easily. Thus, this DOF is eliminated and the direction navigator is compensated by wheels (Fig. 11). Therefore, as Fig. 13 shows,

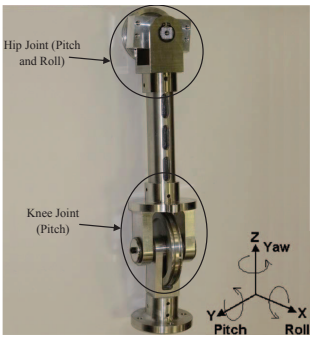

Fig. 13. Hip and Knee

TABLE VIII
LOWER-BODY ACTUATORS

Joint	Joint Axis	Driver	Max Torque *(Nm)*	Ratio (Driven/Driver)
Hip	Pitch	Maxon[a] (Brake)[b]	28.00	2.21/1
	Roll	Maxon[c] (Brake)[d]	39.28	1.36/1
Knee	Pitch	Maxon[c] (Brake)[d]	39.28	1.88/1
Ankle	Pitch	Maxon[c] (Brake)[d]	39.28	2.28/1
	Roll	Maxon[c] (Brake)[d]	39.28	1.88/1
Wheeled Base	Roll	Maxon[e]	3.11	2/1

hip joint was designed to rotate around two intersected axes of pitch and roll to simplify the complicity of control system.

The height of the lower body is designed to have similar height to upper-body's in order to follow human's proportions. Accordingly, since the box height is more than one-forth of robot's proportions, the thigh length is formulated in half size of shank (Fig. 11). Additionally, the hip-pitch axis is located in middle of Nancy's height in order to facilitate Nancy's crouching and bending motions naturally and smoothly using belt-pulley mechanism.

V. CONCLUSION

In the presented work, the mechanical design of Nancy, a social robot has been introduced. To make Nancy capable to mimic human's motions, 32 DOFs and Bowden cable-pulley mechanism have been considered. In order to simplify the system kinematics, all the joints have been designed to have intersected axes. As a result, the distance parameters have been eliminated in kinematic and dynamic analysis. In addition, the scapula joint has been designed to facilitate the imitation of human's social monitions, especially the hugging motion. In the future work, we aim to integrate the control system, artificial intelligence and human-like skin to improve the interaction between Nancy and the environments.

[a] 136198, EC 45, 45 mm, brushless, 150 W, Maxon, Switzerland.

[b] 223101, Planetary Gearhead GP 52, C 52 mm, 4-30 Nm, Ceramic Version, Maxon, Switzerland.

[c] 136207, EC-max 45, 45 mm, brushless, 250 W, Maxon, Switzerland.

[d] 110507, Planetary Gearhead GP 62, C 62 mm, 8-50 Nm, Maxon, Switzerland.

[e] 310009, RE 30, 30 mm, Graphite Brushes, 60 Watt, Maxon, Switzerland.

REFERENCES

[1] G. Wyeth, D. Kee, M. Wagstaff, N. Brewer, J. Stirzaker, T. Cartwright, and B. Bebel, "Design of an autonomous humanoid robot," in *Proceedings of the Australian Conference on Robotics and Automation*, pp. 14–15, Citeseer, 2001.

[2] Y. Ogura, H. Aikawa, K. Shimomura, H. Kondo, A. Morishima, H. ok Lim, and A. Takanishi, "Development of a new humanoid robot wabian-2," in *Proceedings of the 2006 IEEE International Conference on Robotics and Automation*, no. 76–81, IEEE, May 2006.

[3] S. Lohmeier, T. Buschmann, and H. Ulbrich, "Humanoid robot lola," in *Proceedings of the 2009 International Conference on Robotics and Automation*, pp. 775–780, IEEE, 2009.

[4] G. Metta, G. Sandini, D. Vernon, L. Natale, and F. Nori, "The iCub humanoid robot: an open platform for research in embodied cognition," in *Proceedings of the 8th Workshop on Performance Metrics for Intelligent Systems*, pp. 50–56, ACM, 2008.

[5] J. Kim, I. Park, and J. Oh, "Design and Walking Control of the Humanoid Robot, KHR-2 (KAIST Humanoid Robot-2)," in *Proceedings of International Conference on Control, Automation and Systems*, pp. 1540–1543, Citeseer, 2004.

[6] I. Park, J. Kim, S. Park, and J. Oh, "Development of humanoid robot platform KHR-2 (KAIST Humanoid Robot-2)," in *The 4th IEEE/RAS International Conference on Humanoid Robots*, vol. 1, pp. 292–310, IEEE, 2005.

[7] J. Kim, I. Park, J. Lee, M. Kim, B. Cho, and J. Oh, "System design and dynamic walking of humanoid robot KHR-2," in *Proceedings of the 2005 IEEE International Conference on Robotics and Automation*, pp. 1431–1436, IEEE, 2006.

[8] Y. Sakagami, R. Watanabe, C. Aoyama, S. Matsunaga, N. Higaki, and K. Fujimura, "The intelligent asimo: System overview and integration," in *Proceedings of the 2002 IEEE/RSJ International Conference on Intelligent Robots and Systems*, vol. 3, pp. 2478–2483, IEEE, 2002.

[9] T. Isozumi, K. Akachi, S. Ota, F. Kanehiro, K. Kaneko, and H. Hirkawa, "Humanoid Robot HRP-2," *Nippon Robotto Gakkai Gakujutsu Koenkai Yokoshu (CD-ROM)*, vol. 21, p. 3A32, 2003.

[10] K. Kaneko, K. Harada, F. Kanehiro, G. Miyamori, and K. Akachi, "Humanoid robot HRP-3," in *Proceedings of the 2008 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp. 2471–2478, IEEE, 2008.

[11] S. Ge, "Social Robotics: Integrating advances in engineering and computer science," in *Proceedings of Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology International Conference*, pp. 9–12, 2007.

[12] I. Boblan, R. Bannasch, H. Schwenk, F. Prietzel, L. Miertsch, and A. Schulz, "A human-like robot hand and arm with fluidic muscles: Biologically inspired construction and functionality," *Embodied Artificial Intelligence*, pp. 629–629, 2004.

[13] I. Boblan and A. Schulz, "A Humanoid Muscle Robot Torso with Biologically Inspired Construction," *Proceedings of ISR/ROBOTIK 2010*, 2010.

[14] D. Hobbelen, T. de Boer, and M. Wisse, "System overview of bipedal robots flame and tulip: Tailor-made for limit cycle walking," in *Proceedings of the 2008 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp. 2486–2491, IEEE, 2008.

[15] K. Fukui, K. Nishikawa, T. Kuwae, H. Takanobu, T. Mochida, M. Honda, and A. Takanishi, "Development of a new human-like talking robot for human vocal mimicry," in *Proceedings of the 2005 IEEE International Conference on Robotics and Automation*, pp. 1437–1442, IEEE, 2006.

[16] H. Takanobu, K. Nakamura, A. Takanishi, K. Ohtsuki, D. Ozawa, M. Ohnishi, and A. Okino, "Human skull robot as a mechanical patient simulator for mouth opening and closing training," in *Proceedings of the 2001 IEEE/RSJ International Conference on Intelligent Robots and Systems*, vol. 4, pp. 2154–2159, IEEE, 2002.

[17] Y. Hosoda, S. Egawa, J. Tamamoto, K. Yamamoto, R. Nakamura, and M. Togami, "Basic design of human-symbiotic robot EMIEW," in *Proceedings of the 2006 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp. 5079–5084, IEEE, 2007.